WGCPARIS2015
WORLD GAS CONFERENCE
"GROWING TOGETHER TOWARDS A FRIENDLY PLANET"

26th World Gas Conference | 1-5 June 2015 | Paris, France

Gas Interchangeability Study and Resulting NYSEARCH RANGE™ Model for Installed Residential Appliances

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Background

North American natural gas utilities and their customers are benefiting from a new diversity in supply sources. Shale gas, coal bed methane, imported liquefied natural gas (LNG), and bio-derived gases have entered the natural gas distribution system in many regions. These supplies can have compositions that differ from traditional gases that have been distributed. Since gas composition changes can affect the performance of end-use equipment, new supplies must be evaluated to ensure that they are "interchangeable" with the historical gases that have been used for equipment design and adjustment. Interchangeability is "the ability to substitute one gaseous fuel for another in a combustion application without materially changing operational safety, efficiency, performance or materially increasing air pollutant emissions"[1].

Two types of analyses have commonly been used in North America to predict the interchangeability of fuel gases: a single index method (the Wobbe number) and two multiple index methods (the AGA[2] and Weaver[3] Indices). The Wobbe number is representative of the fuel energy input rate to combustion equipment when the gas supply pressure is held constant (as is typical of residential appliances). The multiple index methods predict whether flame characteristics (lifting, yellow tipping, flashback, and incomplete combustion) will be acceptable when new gas supplies ("substitute" gases) are introduced to burners that have been set up to burn historical supplies ("adjustment" gases). These methods were developed primarily through laboratory testing of burners and appliances.

The North American natural gas industry did not anticipate the fast pace of changeover to the wide range of natural gas supplies from domestic sources that happened in the mid to late 2000s, but it did anticipate that it would happen and that it would have an impact. In the early 2000s, industry and regulatory personnel formed the Natural Gas Council Interchangeability Work Group (known as NGC+) to address issues associated with changing supplies. This group established interim numerical guidelines for interchangeability. They also recommended that additional data be collected to characterize the impact of changing gas supplies on end use equipment, including residential appliances[1].

Through a research consortium known as NYSEARCH, representing (20) natural gas utilities, the North American natural gas industry responded to key NGC+ recommendations. The commissioned project, discussed herein, reflected concerns about in-service residential appliances due to the potential sensitivity of this class of equipment to gas composition changes. Based on prior work, it was understood that certain residential appliances are sensitive to changes in natural gas composition due to design characteristics, adjustment practices, or lack of maintenance. Furthermore, it was recognized that customer attention to ongoing maintenance of their appliances is often limited. Thus, performance checks and adjustments for many in-service appliances are infrequent.

One of the drivers for this project related to the geographic diversity of the participants and the varying populations of appliances that could be studied. The program sponsors in North America made special efforts to collect data from differing regions for appliances in operation in customers' homes. Additionally, after the initial field test work, other gas companies joined and provided their own test data collected at high elevations to supplement the NYSEARCH field test data.

As a sub-organization of the Northeast Gas Association, NYSEARCH's mission is to identify and address the needs of its members through research, development and demonstration. It accomplishes this mission by finding experts with experience and know-how from around the world. In this case, NYSEARCH utilized the expertise and services of Environ Corporation and later its spinoff company, etaPartners, whose team had performed similar research studies for individual gas companies facing challenges associated with the impacts of changing gas supplies. The team from etaPartners had worked with many gas companies in the U.S. and Canada to address interchangeability issues associated with the distribution of imported LNGs, shale gas, coal bed methane and bio-derived gases. From the business model that NYSEARCH uses, a funded project and the specific detailed findings are generally shared with the sponsors and limited for non-funding organizations. In this project, in addition to several other deliverables, etaPartners produced for NYSEARCH a product that could be applied by the funders and also provided commercially as an online analysis tool for use by others interested in the impact of changing gas supplies on in-service residential appliances. This product, known as the NYSEARCH RANGE™ model, is available at www.nysearch.org.

Aims

NYSEARCH engaged Environ/etaPartners to conduct, with (13) of its members, a geographically diverse field study that quantified the performance of different populations of installed and in-service residential appliances. It also determined the extent to which potentially sensitive appliances exist. Performance in this study refers to flame quality (including problems such as lifting and yellow tipping) as well as the levels of carbon monoxide (CO) and NO_x emissions.

Next, the team conducted laboratory testing of appliances that were identified as being potentially sensitive to changing gas quality. Tests were performed on models that were retrieved from field test sites. Each was initially evaluated "as found" and then was subjected to a range of common adjustments to examine possible variations in performance. The purpose of this testing was to provide data to develop guidelines for accommodating changing gas compositions and to determine the most effective gas interchangeability parameters.

Following the research and data collection effort, the funding group developed a spreadsheet-based interchangeability model. This model projects the performance of the in-service appliance population when new gas compositions are supplied. Results include the distribution of carbon monoxide emissions and flame characteristics for in-service populations of four different appliances types: water heaters, ovens, boilers, and furnaces.

eta-Partners and NYSEARCH worked interactively to produce a practical tool that predicts appliance population performance given a range of input gas compositions. This tool enables assessment of specific user-defined gas compositions and is available for use by industry. A subset of the NYSEARCH funding group also carried the project one step further by examining with etaPartners how the results may impact indoor air quality and, therefore, customer safety. Finally, NYSEARCH members are currently expanding the model for use with other potential energy supplies such as hydrogen.

Methods

At the start of the project, eta Partners described important safety and operability related flame characteristics. When natural gas compositions change, the primary combustion phenomena of interest for appliances are incomplete combustion (CO emissions), soot formation (yellow tipping), and flame lifting.

- *Lifting* is the movement of the flame front downstream and away from burner ports as a result of decreases in flame speed relative to flow velocity. This condition can cause delayed or failed ignition of an appliance burner. With delayed ignition, flames can temporarily flash outside of the appliance enclosure. Lifting can also produce elevated carbon monoxide emissions.
- *Yellow tipping* is the generation of soot particles within a flame that radiate incandescently, exhibiting a yellow color. If severe, this condition can result in soot deposition on downstream surfaces (e. g., heat exchangers or flues) and can ultimately cause flue gas passages to be restricted or blocked.
- *Incomplete combustion occurs* when carbon in the fuel gas is not fully oxidized to carbon dioxide. The consequence is elevated levels of carbon monoxide emitted in the exhaust gases by certain appliances. Should CO be emitted by an appliance that is not vented into a flue pipe or by a vented appliance experiencing a flue failure, CO levels inside the structure may rise.

At the outset, based on prior industry studies, it was clear that the Wobbe number $Wobbe = \frac{Heating Value}{\sqrt{Specific Gravity}}$ was an important index to consider. Increases in gas Wobbe number may have the following impacts on appliance performance:

- Energy input (firing rate) can increase
- Excess air level can decrease
- Carbon monoxide emissions can increase
- Yellow tipping can increase
- NO_x emissions can increase or decrease, depending on burner design and adjustment

- Heat exchanger temperatures can rise

Decreases in Wobbe number gases generally have the opposite effects. However, flame lifting can increase and, therefore, carbon monoxide emissions can increase. While recognizing the significance of the Wobbe number in interchangeability assessments, the project team maintained an open perspective regarding which additional gas quality parameters influence appliance performance.

Field Testing of Appliances

Three of the sponsoring Local Distribution Companies (LDCs), located in northeastern and western states of the US, participated in the field performance survey. Experienced service staff from each of the LDCs conducted field inspection and performance measurement work on customers' appliances. These customers were generally selected through a random method in order to obtain a database that is representative of the entire appliance population within these geographically diverse service areas. Specific field measurements included gas flow rate; flue gas O_2, CO, and NO_x concentrations; gas manifold pressure; and flame characteristics (utilizing the AGA flame code as defined in Table 1 and Figure 1). Appliance performance measurements were collected using portable flue gas analyzers. Performance test procedures for each appliance type were structured to be consistent with the American National Standards Institute (ANSI) certification protocol (e.g., Z21.10.1 for water heaters), while also being representative of typical residential operation.

AGA Flame Code	Description
-5	Distinct yellow in outer mantles, or large volumes of luminous yellow tips on inner cones. Flames deposit soot on impingement.
-4	Slight yellow streaming in outer mantles, or yellow fringes on tops on inner cones. Flames deposit no soot on impingement.
-3	Inner cones broken at top, lazy wavering flames.
-2	Faint inner cones.
-1	Inner cones visible, very soft tips.
0	Inner cones rounded, soft tips.
+1	Inner cones and tips distinct.
+2	Inner cones distinct and pointed.
+3	Short inner cones, flames may be noisy.
+4	Flames tend to lift from ports, but become stable after short period of operation.
+5	Flames lifting from ports, with no flame on 25% or more of the ports.

Table 1: AGA Flame Code Rating System

Figure 1: Flames Characteristic for AGA Flame Code Ratings

Each of the LDCs also monitored gas compositions being distributed during the survey work. A histogram of Wobbe numbers for gases distributed during the field tests is provided in Figure 2. The median Wobbe number is 1337 Btu/ft^3 (49.8 MJ/m^3), while 85% of the data points are between Wobbe numbers of 1323 (49.3 MJ/m^3) and 1344 (50.1 MJ/m^3). The full range extended from Wobbe numbers of 1296 (48.3 MJ/m^3) to 1420 (52.9 MJ/m^3). This distribution is similar to that developed by the NCC+ Interchangeability Work Group to characterize North American natural gas supplies.

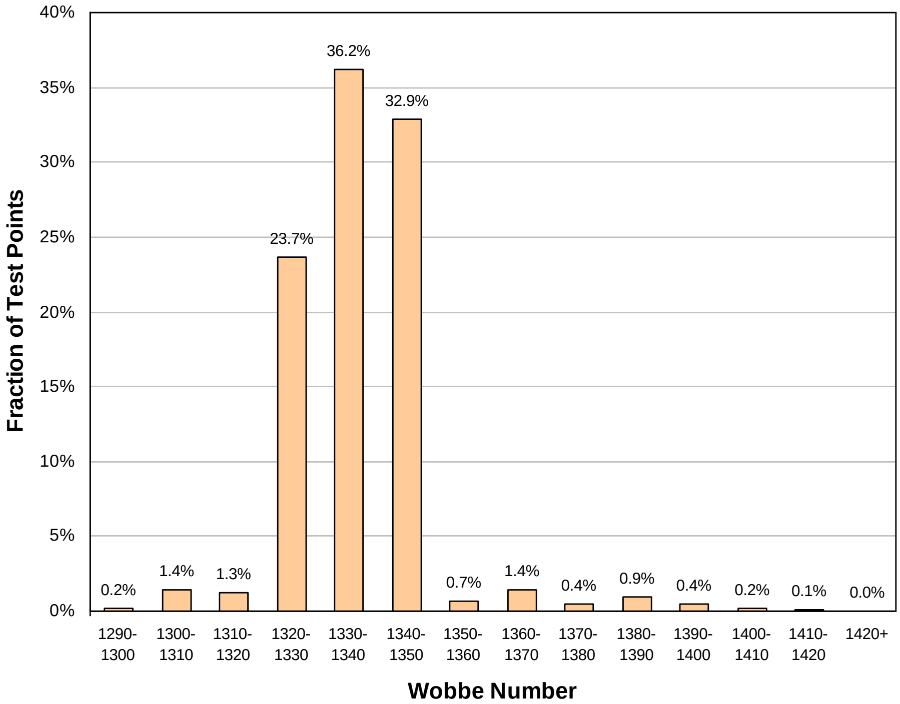


Figure 2: Distribution of Wobbe Number during the Field Tests

The distribution of appliance types within the database collected through the field tests is provided in Figure 3. About 47% of the appliances tested were domestic water heaters. The second largest category consists of heating appliances. Warm air furnaces and boilers, combined, constitute about 30% of the database. Next come ovens at about 21%. This distribution is reasonably consistent with recent appliance shipments in the US. The category labeled "Other", at 2%, includes appliances such as clothes dryers, space heaters and fireplace logs.

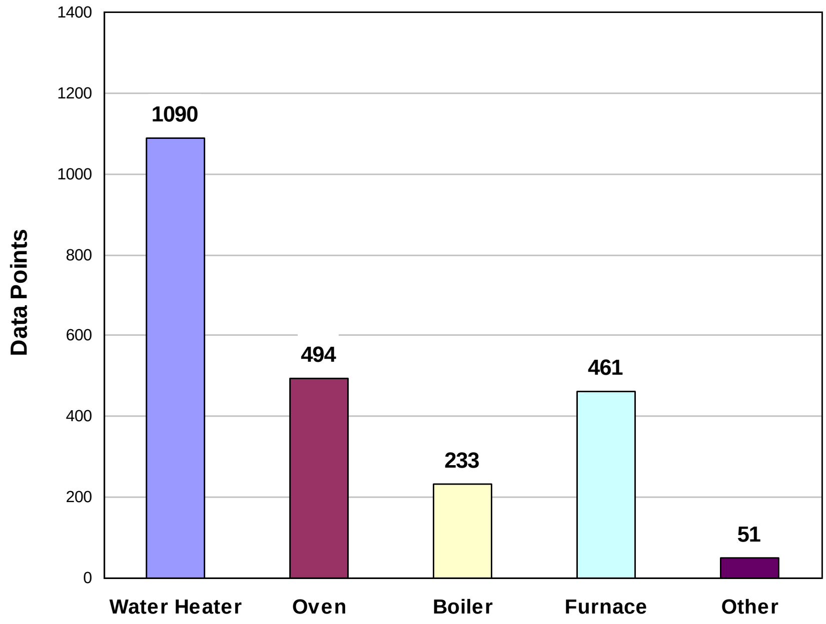


Figure 3: Distribution of Appliance Types

Appliance ages were determined from the appliance nameplate or through input from the customers. About 27% of the sampled appliances are relatively new (< 5 years old), while 17% are over (20) years old.

Laboratory Testing of Appliances

Appliances: The tests, conducted in etaPartners' laboratory, were structured to assess the impact of gas composition changes on the performance of in-service appliances. Most of the specific units tested were identified from the field test database and then retrieved from customers' homes. In selecting the appliances, emphasis was placed on testing units that are commonly found in service areas. Several additional appliances were selected to address specific combustion issues and to evaluate the effects of elevation on interchangeability. A total of eighteen appliances were tested: (3) water heaters, (6) warm air furnaces, (5) boilers, (3) ovens, and (1) space heater.

Test Gases: The performance of each unit was measured when operating on a wide variety of gas compositions. The funding group selected (14) different gases to include in the testing. These are representative of traditional supplies, unconventional supplies (including shale gas, coal-bed methane, and LNG), stretch gases having compositions that extend beyond the range of expected deliveries, and several gases constructed to evaluate analytical methods for assessing interchangeability. The latter gases are two-component blends that could also serve as limit gases in possible future appliance certification tests.

In Figure 4, the test gases are positioned on a plot of hydrogen-to-carbon ratio (H/C) versus Wobbe number. The H/C value is the ratio of hydrogen atoms to carbon atoms in the hydrocarbon species. It serves as a measure of the higher molecular weight hydrocarbon content.

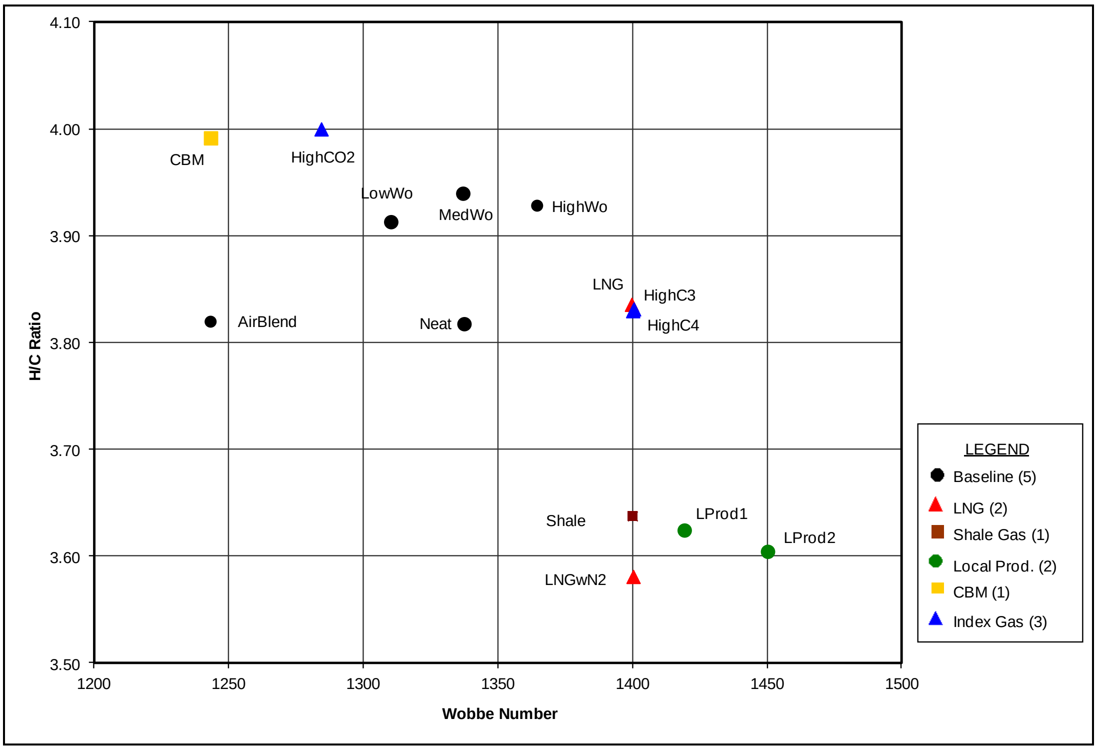


Figure 4: Laboratory Test Gas Characteristics

Procedure: Initially, each appliance was tested in the "as received" condition with gas compositions that are close to those in use during the corresponding field test. Then, each appliance was tested over the full range of gas compositions. Next, a subset of appliances (having either specific performance issues of interest or available air adjustment shutters) was tested to closely examine the effectiveness of gas interchangeability indices (e.g., AGA and Weaver). The influence of appliance adjustments, such as air shutter position, was also determined. Finally, after diagnosing and correcting specific appliance performance problems, each appliance was tested with the full gas composition range. Collectively, these results document the response of improperly and properly tuned appliances to specific gas composition changes.

Key results from prior interchangeability testing conducted by several sponsoring and collaborating LDCs were merged with the laboratory data from this project. The combined dataset covers testing at four elevations, ranging from about sea level to 10,000 feet (3048 meters).

Results

Through the field survey, performance characteristics of (2329) residential appliances were documented. Appliance CO emissions were sorted into three broad performance categories based on ANSI standards. In certification tests, water heaters, boilers, and furnaces must achieve CO emissions below 400 ppmv, air-free, while ovens must be below 800 ppmv, air free. The resulting categories are as follows:

- ***Compliant:*** CO emissions below 50% of the ANSI standard (ovens less than 400 ppmv, air free; all other appliances less than 200 ppmv, air free).
- ***Marginally-compliant:*** CO emissions between 50% and 100% of the ANSI standard (ovens between 400 and 800 ppmv, air free; all other appliances between 200 and 400 ppmv, air free).
- ***Non-compliant:*** CO emissions above the ANSI standard (ovens in excess of 800 ppmv, air-free; all other appliances in excess of 400 ppmv, air free).

Field Test Results

Carbon Monoxide Emissions: A histogram of CO emissions (relative to the ANSI standards) is provided in Figure 5. As indicated, most equipment was found to be producing relatively low emission levels. However, a smaller percentage was producing elevated CO emissions. The percentage of appliances in the non-compliant category (where the ANSI Standard is exceeded) is low, but not insignificant. Some appliances were generating CO levels at the flue that were sufficiently high to be of concern from a safety perspective. These units were either adjusted or shut down at the time of the survey. Causes for elevated CO levels included over-firing, combustion air passage restrictions, flue gas passage restrictions, flame impingement on cooler surfaces, and burner mal-adjustment.

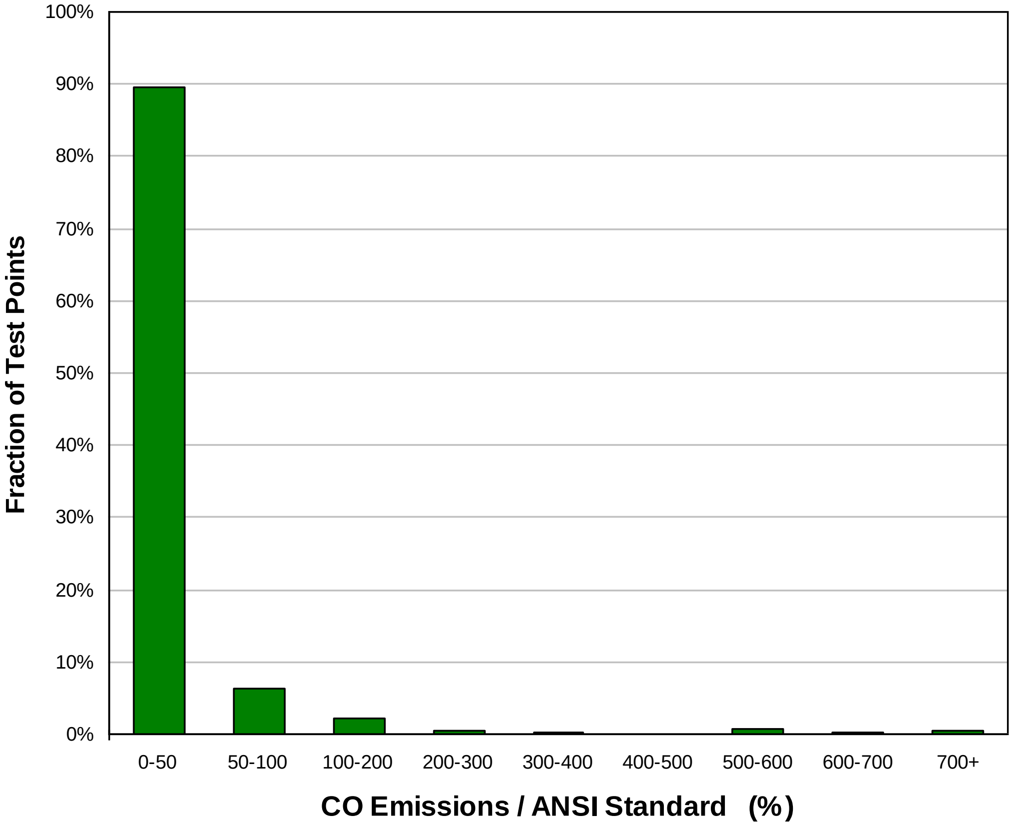


Figure 5: CO Emissions Relative to ANSI Standards

Flame Characteristics: The distribution of AGA Flame Code measurements among all appliance types is provided in Figure 6. A good state of burner adjustment is represented by values from -2 to +2. About 88% of the appliances sampled are within this range. The distribution is skewed towards the negative AGA Flame Codes (55% of the observations are negative, 32% are neutral, and 13% are positive). Negative ratings indicate a "soft" state of adjustment where primary combustion air provided to the burner is reduced. However, only about 2% of the appliances exhibited yellow tipping (-4 and -5 ratings).

AGA Flame Codes of +4 and +5 indicated the occurrence of flame lifting and a +3 rating indicates that lifting is imminent. This phenomenon can cause elevated CO emissions. As shown in Figure 6, less than 1% of the sampled appliances were operating with an AGA Flame Code in the range of +3 to +5.

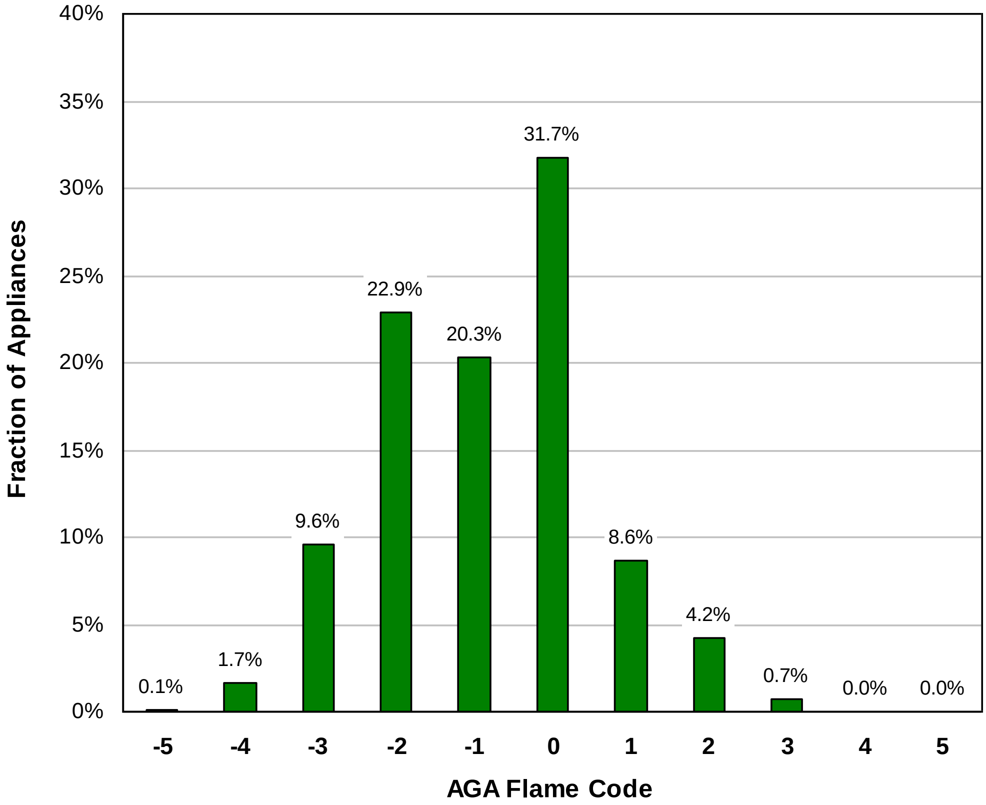


Figure 6: The distribution of AGA Flame Code

The field test results confirm that most appliances are properly adjusted and are performing acceptably. With 90% confidence, it can be concluded that between 88.1 and 90.8 percent of the entire population of appliances in these service areas emit carbon monoxide at concentrations that are below 50% of the corresponding ANSI certification standards. Furthermore, between 86.3 and 89.2 percent of the appliance population operates with AGA Flame Codes between +2 and -2. These values are characteristic of good burner design and adjustment as neither yellow tipping nor lifting phenomena are present.

However, a small but significant proportion (between 5.3 and 7.5%) of the appliance population operates with CO emission concentrations at the flue between 50 and 100 percent of the ANSI standard. In addition, between 3.4 and 5.2 percent of appliances operate with CO emissions at the flue in excess of the ANSI standard. Unvented appliances in this category or appliances with deficient venting systems could introduce elevated CO concentrations into occupied spaces, potentially creating a health hazard.

Laboratory Test Results

Illustrative laboratory test results are provided below for three storage-type water heaters and a range-top burner. The "as received" performance for each of the water heaters is provided in Figure 7. In this graph of CO emissions vs. Wobbe number, each data point represents operation with a different test gas. Due to the wide range in CO values, a logarithmic scale is utilized. As indicated, water heater 1 exhibits excellent performance across the full range of gases. The other two experience increases in CO as the gas Wobbe number increases. Water heater 2 reaches the ANSI limit (red line) at a Wobbe number of about 1450 (54.0 MJ/m^3), while water heater 3 reaches this mark at a value of about 1380 (51.4 MJ/m^3). For the latter two units, the Wobbe number was effective in correlating the variations in CO concentration.

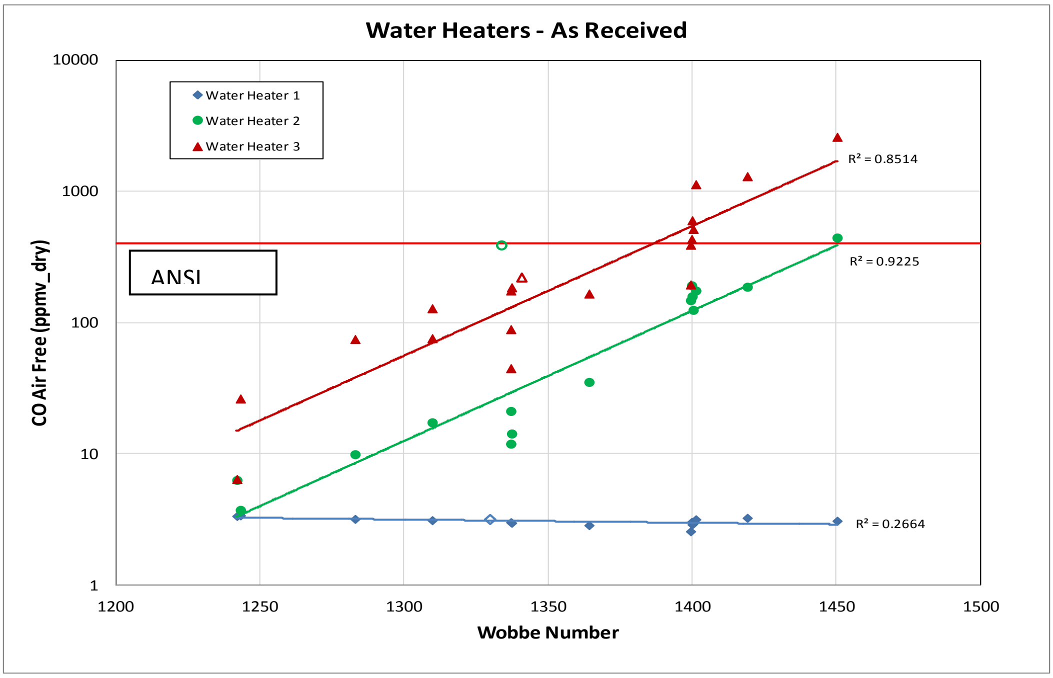


Figure 7: Water Heater CO Emissions – As Received

The effect of changes in the hydrogen-to-carbon ratio on flame characteristics is illustrated in Figure 8. These photos of a range-top burner operating on two different 1400 Wobbe number (52.2 MJ/m^3) gases clearly show increased yellow tipping as H/C decreases.

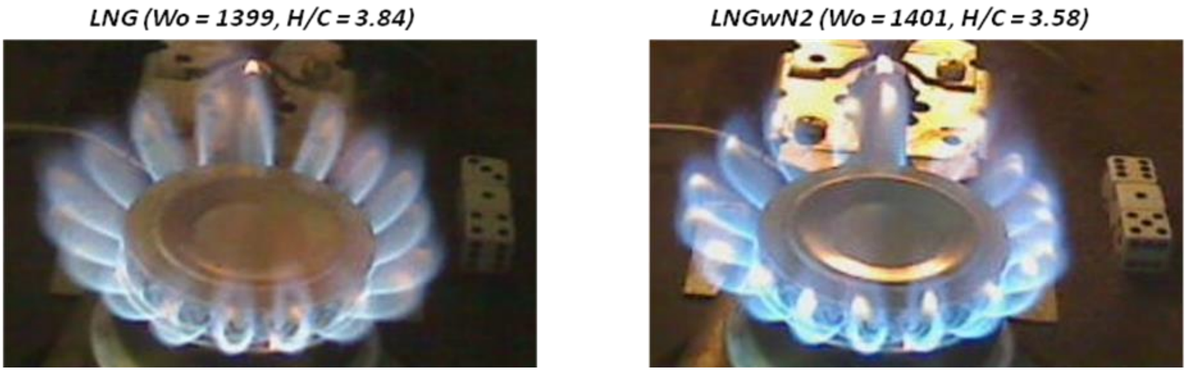


Figure 8: Effect of Hydrogen-to-carbon Ratio on Yellow Tipping

Analysis of the entire set of laboratory data revealed that two key natural gas parameters can be utilized to correlate appliance performance changes:

- The ***Wobbe number*** quantifies the change in firing rate and was found to be the primary variable affecting appliance performance characteristics.
- The ***hydrogen-to-carbon ratio*** characterizes the concentrations of higher molecular weight hydrocarbons (ethane, propane, and butane). Relative to methane these species generally increase flame temperatures, laminar flame speeds, and soot formation rates. Over the range of fuels evaluated, H/C was found to have a secondary impact on appliance performance.

NYSEARCH RANGE^{TM} Model

An in-service appliance database was assembled by merging field performance data collected in the NYSEARCH project with similar data previously collected by one of the sponsoring LDCs. This dataset includes performance characteristics (gas flow rate; flue gas O_2, CO, and NO_x concentrations; gas manifold pressure; and flame characteristics) and natural gas parameters (Wobbe number, H/C) from field tests conducted on 2536 in-service residential appliances.

To estimate the impact of gas composition changes on performance, correlations were developed from the laboratory test results for each main appliance category (i.e., ovens, water heaters, furnaces, and boilers). These correlations capture the impact of Wobbe number and hydrogen-to-carbon ratio on CO emissions and AGA Flame Code. They allow the prediction of appliance performance on a new gas supply, given an initial performance level on a known gas supply. The gases need only be characterized by their Wobbe numbers and the hydrogen-to-carbon ratios.

To evaluate performance changes for populations of appliances, the laboratory-based CO and AGA Flame Code correlations were applied to the field performance database. The result is the project's spreadsheet-based interchangeability assessment program.

The NYSEARCH RANGE™ (Range of Acceptability for Natural Gas Equipment) model allows specification of a baseline gas composition (representing historical deliveries or a target adjustment gas) and up to four other gas compositions (representing new or proposed deliveries). For each gas composition specified, the performance of the appliance population is determined by applying the project-derived correlations to each individual appliance in the database. Then histograms for CO emissions and AGA flame code are produced for each gas composition. Finally, a range of acceptability graph (Wobbe number vs. H/C ratio) is generated based on limits set for the percentage of appliances in each of the performance categories (CO emissions, yellow tipping and lifting). These limits can be modified based on company policy, regulation, or historical practice.

Model output: Illustrative output from the model is provided in Figures 9 and 10. The former contains CO histograms for the baseline population as well as the four substitute gases. The Wobbe number and H/C ratio for each gas are provided in the legend. The latter figure contains the AGA Flame Code histograms. In this example, increasing gas Wobbe numbers from 1281 (47.7 MJ/m^3) to 1412 (52.6 MJ/m^3) progressively raises the percentage of appliances in the non-compliant CO category from 2.7 to 6.9 and shifts the AGA Flame Codes to lower values.

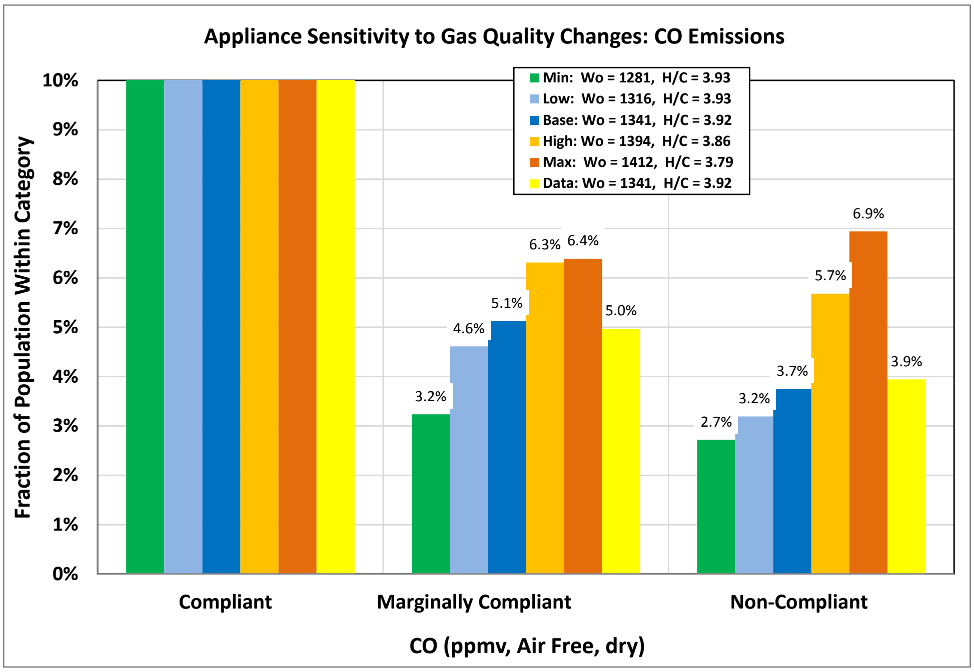


Figure 9: CO Histograms for Appliance Population

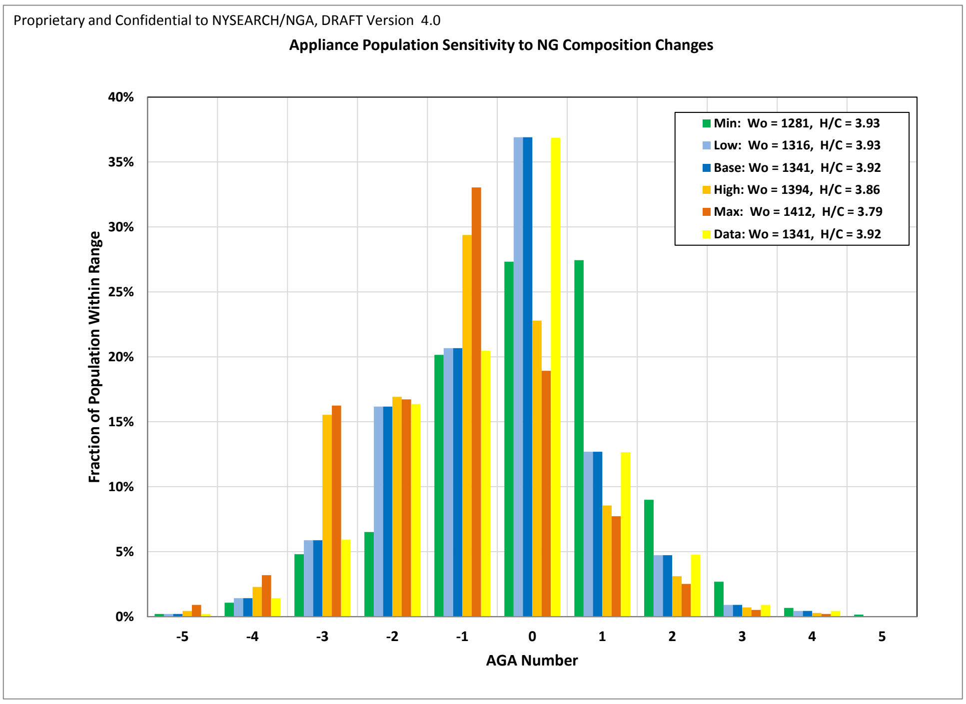
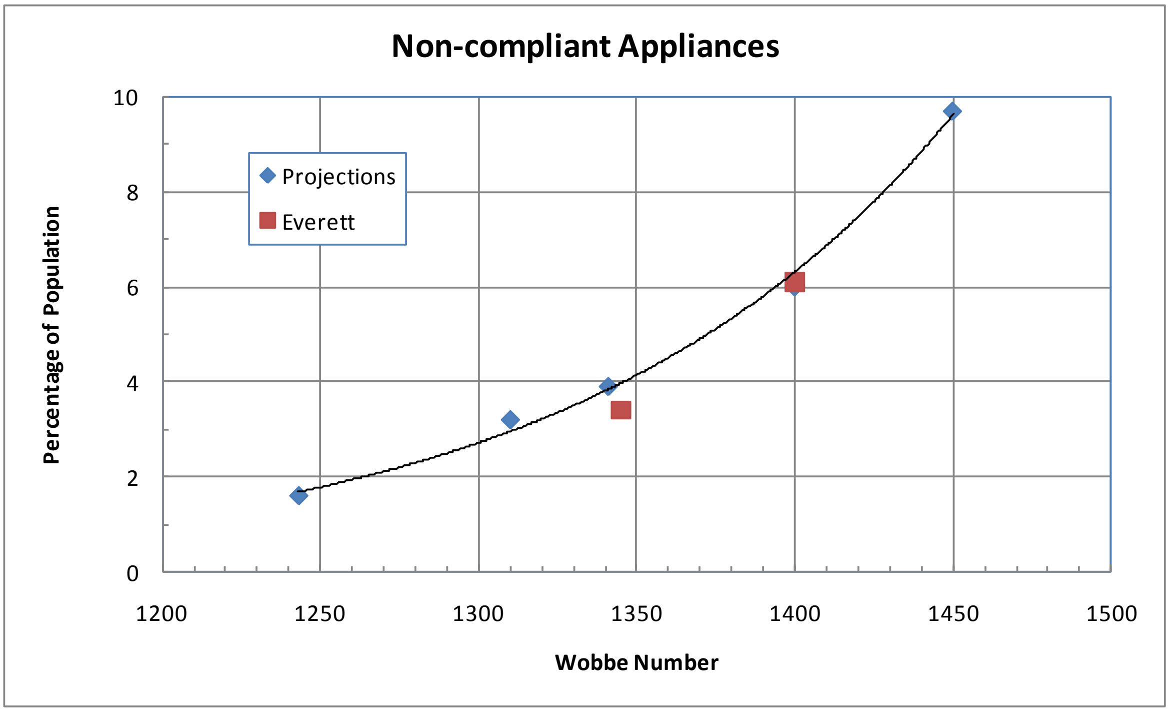


Figure 10: AGA Flame Code Histograms for Appliance Population

Model Validation: The NYSEARCH RANGE™ model's predictions were compared to appliance field data collected in the early 1990s when LNG from Algeria was introduced through the Everett LNG import terminal near Boston, MA. In Figure 11, the projected non-compliant CO percentages for the appliance population are plotted as a function of Wobbe number. Also provided on this plot are results from residential appliance field data collected before and after the LNG was introduced. The 1345 (50.1 MJ/m^3) Wobbe point is from data collected when domestic natural gas was being distributed, while the 1400 (52.2 MJ/m^3) Wobbe point is for distribution of imported LNG. The excellent agreement between the projections and the field data validates the model's fundamental assumptions and confirms the applicability of the model results to other service areas.

Figure 11: Comparison of NYSEARCH RANGE™ Projections with Field Data



Range of Acceptability: The Limit Analysis Graph defines a range of acceptability for gas supplies based on values of the Wobbe number and the hydrogen-to-carbon ratio. Specific limit curves are calculated for appliance performance with respect to CO emissions, yellow tipping and flame lifting. Selection of appropriate upper and lower boundaries for the range of acceptability can be based on equipment safety and operability experience. Specific decisions regarding an appropriate range of acceptability are the responsibility of individual LDCs. An illustrative analysis is provided below.

From field performance surveys of appliances conducted in this project, prior field surveys, and the successful distribution of imported LNG, it is reasonable to conclude that a 6% limit on the proportion of appliances exceeding the ANSI CO limit would not cause a significant increase in risk to customers. That is not to say that the industry should not strive to lower this percentage. Rather it is the recognition that, in most situations, elevated CO emissions alone do not create a direct hazard. Other elements, such as a flue failures or low ventilation rates, are required to affect the health of customers.

For the lower boundary, the impacts of flame lifting on customer safety and equipment operability must be considered. Lifting-induced CO emissions are of most concern when experienced in combination with flue failures or low ventilation rates. However, significant lifting alone can prevent appliance flames from stabilizing and thereby cause failed ignition. As increasing percentages of appliances experience lifting, the impact on appliance population operability is likely to become critical before significant overall safety impacts are experienced. Thus, to avoid significant increases in service calls, the percentage of appliance experiencing lifting is to be maintained below about 1%. Only about 10% of these lifting appliances are projected to experience +5 AGA flames.

Applying these guidelines, the range of acceptability is illustrated in Figure 12. Four potential boundaries are plotted, based on the following limits:

- Two limit curves for CO (red line set at 6% of appliances exceeding the ANSI standard, orange line set at 15 % exceeding half of the ANSI standard). These represent potential upper boundaries on the range of acceptability.
- A limit curve for yellow tipping (green line set at 5% of appliances exhibiting yellow tipping). This represents another potential upper boundary.
- A limit curve for lifting (blue line set at 1% of appliances exhibiting lifting). This represents a potential lower boundary.

Maintaining gas characteristics between the red and blue curves would satisfy all of the selected limits.

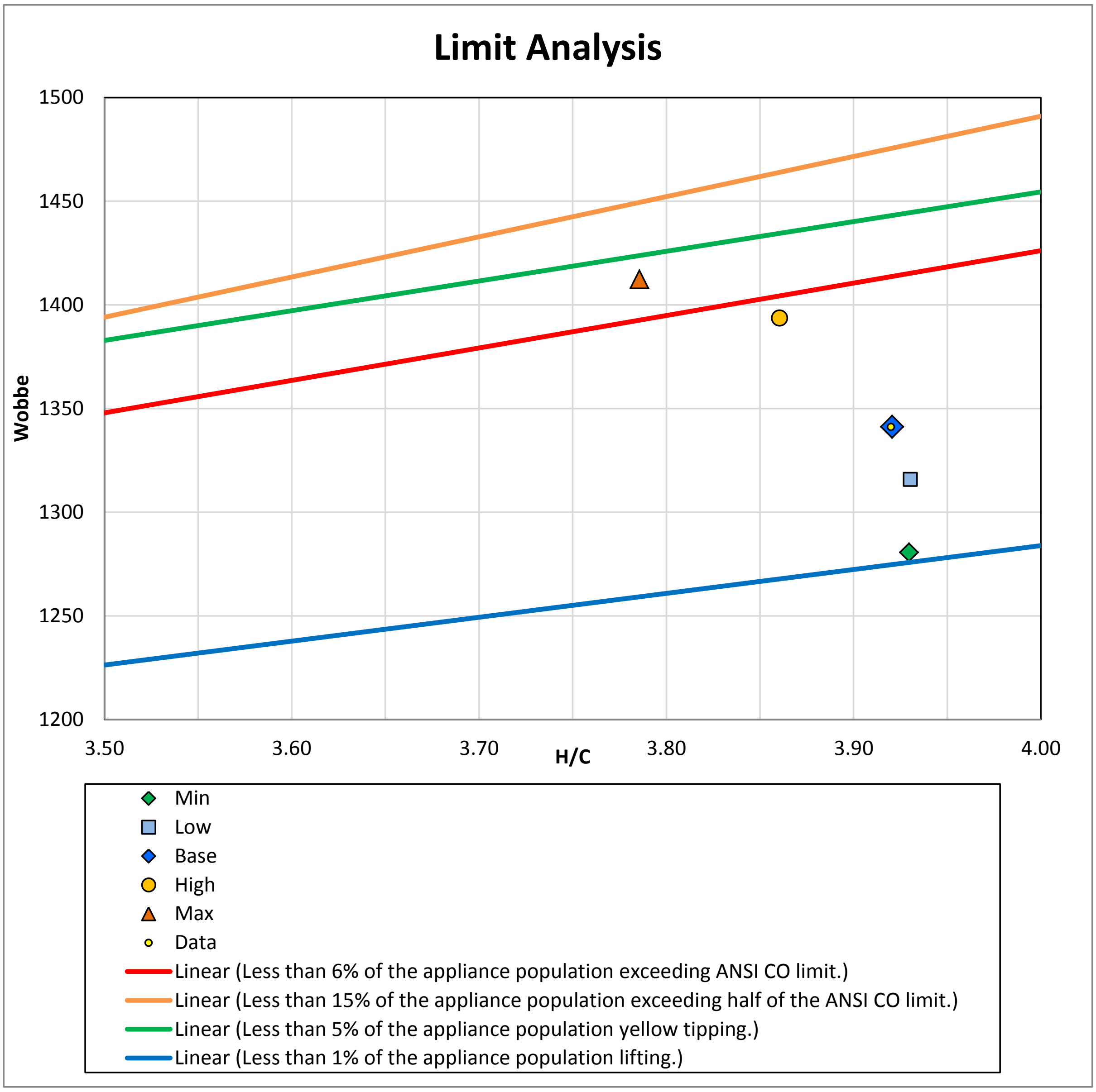


Figure 12: Range of Acceptability Analysis

Indoor Air Quality Analysis: The NYSEARCH RANGE™ model also incorporates an analysis of potential indoor air quality impacts. A spreadsheet-based room mixing model was applied to evaluate indoor CO concentrations that result when appliance flue gases are discharged into rooms (e.g., unvented appliances or vented appliances experiencing a flue failure). Values for the key independent variables (i.e., flue gas CO concentration, room size, room ventilation rate) were systematically varied to determine combinations that produce indoor CO concentrations above recognized health-related CO concentration limits (e.g., US OSHA and EPA limits).These results were applied to assess the risks associated with various levels of carbon monoxide in the flue gases of different appliance types. The mixing model results were then coupled with the appliance population CO predictions to generate room air quality impact factors. Specifically, these numbers represent the percentage of appliances that are expected to generate ambient CO concentrations above 75 ppm if all flue gases are discharged into the room. The 75 ppm threshold corresponds to the EPA's significant harm level based on a 4-hour time-weighted average. This model enhancement enables risk-based decisions to be made regarding gas quality changes.

Conclusions

The field testing of residential appliances indicated that most in-service appliances are properly adjusted and are performing acceptably. However, a small but significant proportion of appliances operate with elevated CO emissions at the flue or undesirable flame characteristics. These appliances can be more sensitive to gas composition changes.

With improved appliance maintenance, the population of in-service appliances will become less sensitive to gas composition changes. For those LDCs not already having effective communications programs in place, it is recommended that enhanced communications with residential customers be initiated. Emphasis should be placed on the need to perform annual maintenance on all gas-fired appliances. Furthermore, service staff should perform CO emissions and flame appearance checks of all gas-fired appliances during each service call.

Analysis of the laboratory data revealed that two key natural gas parameters can be utilized to correlate appliance performance changes: The Wobbe number quantifies the change in firing rate and was found to be the primary variable affecting appliance performance characteristics. The hydrogen-to-carbon ratio characterizes the concentrations of higher molecular weight hydrocarbons and was found to have a secondary impact on appliance performance.

The laboratory testing also confirmed that two- or three-component gas blends can serve as limit gases for appliance certification tests. By strategically placing such gases on the "range of acceptability" boundaries, the performance of new appliances will be validated for the full range of gases to be distributed.

The NYSEARCH RANGE™ model offers a new interchangeability assessment method that focuses on performance of the in-service residential appliance population. It is being applied by natural gas companies in the US and Canada to establish gas quality limits[4] and to design gas processing equipment[5].

Dialogues with gas company decision makers, industry collaborators, and appliance manufacturers have been initiated to convey the project's recommendations. The focus is on best practices for installing and servicing appliances, interchangeability assessment methods for in-service appliances, and appliance certification test methods. The ultimate goal is to optimize practices for appliance design and operation while reducing risks associated with gas composition changes and, thereby, to successfully accommodate a wider range of emerging gas supplies.

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